XIV. SAFIR and In-Space Operations

Introduction

Conceptual application of in-space assembly and servicing to a large infrared telescope such as SAFIR illustrates multiple possible benefits and some significant impacts on design for the telescope and supporting architecture elements. While we believe that autonomous deployment of SAFIR is achievable in the 2015-2020 time frame and thus baseline it, the Vision Mission effort has allowed us to investigate opportunities that in-space operations could bring. This effort has been done in concert with the activities of the Second Loya Jirga conference on in-space capabilities for science. We include this section of the Vision Mission report with the explicit understanding that while the SAFIR fully autonomous baseline is completely credible, in-space operations may be profoundly enabling for new science. Our efforts have benefited strongly from Boeing, which was one of our designated SAFIR Vision Mission industry partners, bringing insights about in-space operations and agents to our study.

Basic Concepts

Assembly in space can provide operational structures much larger than the self-deploying structures accommodated in a single launch vehicle shroud. Improved reliability of deployment can, in principle, be realized through verification of critical functions. If continued access by intervention agents (human-robotic operation) can be realized, then mission assurance or mission extension by maintenance and servicing as well as productivity enhancement by upgrades, can also be realized. Some of the enabling features of this approach have modest impacts to the baseline SAFIR designs but others are significant enough to warrant careful consideration.

For SAFIR, we see one of the main scientific advantages scientific instrument changeout and general observatory refurbishment. These would allow a large investment in the basic optical system to be multiplied by reuse. The baseline mission for SAFIR assumes an observatory that is decommissioned when the science value of the focal plane instruments has been achieved. Since focal plane instrument capabilities are strongly tied to sensor capabilities which are rapidly increasing, reuse of the observatory optical and control system can be highly enabling. The value of such efforts has been clearly proven with HST (Hubble Space Telescope), which in its fifteen-year operational lifetime has hosted several generations of focal plane instruments, each offering entirely new scientific capabilities. For SAFIR, such an opportunity would come after an initial operations cycle, perhaps five years into the mission. We approach this effort with the belief that the Vision goals of astronomy can be well served by use of shared capability systems.

Functional Capabilities Assumed To Be Available For Use

In anticipating the role that human and robotic in-space capabilities may offer SAFIR, it is useful to consider the capabilities that the Vision for Space Exploration may provide. The extent to which the technologies and infrastructures supporting Exploration activities are also available and usable for telescopes and science platforms is an issue having strong implications for mission design trades. This will be addressed in detail in the following sections.

A decade from now, the Exploration Vision may have led us to achieve the first Crew Exploration Vehicle (CEV) flight, but the first human mission to the Moon may be another five years from realization. The robotic capabilities for the Lunar Orbiters and several robotic testbed missions would be operational by then. Mars precursor and testbed missions would also be operational. The James Webb telescope would be in operation, and the Terrestrial Planet Finder may be starting.

This progress will necessitate some advances in human-robotic capabilities during the development phases of the operational programs. Increasing development, commissioning, and use of robotic operations should be expected during the timeframe in which the Shuttle operations are to be retired. Coordination of roles of robots with humans in space should be part of the development of the new CEV systems being brought on-line for operations. While space astronomy in general, and SAFIR in particular, will not develop these capabilities, it is possible to make some general predictions about the capabilities that the Vision will provide, and map those capabilities onto enabling opportunities for SAFIR and other observatories. Specific requirements for human-robotic operations support including in-space assembly and servicing are not clear at this time. However, broad implications can be explored in order to bring the issue of astronomical capabilities into clearer focus. In-space assembly and servicing would require a minimum set of features to be of limited early use to astronomy, and an extensive set of expansion options would be considered as utility and demand come forward.

Among the important systems to be developed for Exploration that can also be used to serve telescope assembly and servicing for a mission like SAFIR are (at least):

- Cranes, robots, and other ‘civil engineering’ tools for system assembly
- Habitation for humans who will be managing the robot fleet and conducting testing
- Permanent collection of testing equipment suitable for structures characterization
- Long-term storage of cryogenic fluids (fuels and purge gases)
- Contamination control approaches, cleaning facilities

Robotic-only operations offer more limited capability compared with coordinated human-robotic operations. Robotic-only operations still involve humans in design and production of the systems and perhaps in ultimate control of mission application at a distance, but the human participants need not be in-situ astronauts. Human-robotic coordinated operations do involve sending humans into space, in order to reduce the latency of sensing and control and the intensity of direct perception and interaction that are so valuable for problem solving and situation assessment in actual EVA hands-on activities. The in-space operations needs and infrastructure support of large space assets like SAFIR, have been recently reviewed by the Loya Jirga II roadmapping team (Thronson; 2005 SPIE 5899).

For the basic capability of in-space assembly and servicing we must consider not merely the presence of mobile agents (robots, astronauts, or coordinated teams) but also the delivery systems to carry them to the worksite venue in space (launch vehicle, guidance, rendezvous and capture), and the supporting systems to keep them functioning (power, communications, guidance and navigation with appropriate actuation systems such as propulsion.) By definition, these capability systems must support the rearrangement of all components from a configuration optimized for shipping (i.e. launch conditions and packaging constraints), into a configuration optimized for mission operation. Therefore, there is a need for structures to hold the supporting agents and components together in proximity and provide environmental protection for all components and all intermediate configurations at the worksite. Productive operations will also require a variety of tools for handling and processing, and test equipment to verify the completion of operational steps and procedures.

This basic capability is minimally adequate for assembly and servicing of a wide variety of client mission systems needed by the Vision for Exploration, e.g., vehicles, habitats, landers, support infrastructure systems, etc. Each particular mission would have to develop and launch everything needed that was not already provided; therefore, the earliest missions to be supported by the capability would have only the most limited support already available. of astronauts for human-robotic coordinated assembly and servicing operations is likely to be met as we meet Exploration needs. Some of these requirements include human launch and return-to-Earth systems, in-space habitat with life support and safety systems, and logistics support. Advanced EVA systems may not be available for in-space use by client missions, however, until after the human missions to the Moon become routine. In view of the increasing sophistication of robot agents, we do not believe this to be a serious impediment.

Robotic-only systems are likely to be operational at various sites in the Earth-Moon vicinity, though the particular arrangement of equipment and infrastructure support systems that would serve the Exploration Vision has yet to be determined. A subset of the systems developed for lunar surface operations could be adapted to serve as a core of the basic capability equipment for in-space assembly and servicing. These systems would be supplemented by in-space unique features such as the zero-gravity tie-down structures, environmental protection, and crawling or close proximity formation-flying for local transport. Power systems, information and data systems, robotic control systems, communications, guidance and navigation systems, and many general-purpose tools that are developed for lunar surface operations could all be repackaged or repurposed for use in support of in-space assembly and servicing.

General Benefits of In-Space Capabilities to Large Telescopes

We begin with a broad-brush overview of the potential value of in-space efforts by humans and robots to large telescope missions. While not focused specifically on SAFIR, this general overview provides context for the importance of such developments in the longer term, and provides the strategic foundation for linkage of space astronomy to in-space capabilities.

Larger aperture: For light collection, and spatial resolution at wavelengths not accessible from the surface of the Earth, large collecting apertures in space represent the future of at least UV, optical, and infrared astronomy. Assembly in space enables the deployment for use of structures that cannot be launched in a single vehicle. In-space capabilities provide the means whereby multiple vehicle payload integration of sophisticated components can be considered. An additional advantage over traditional wholly autonomous mechanical deployments is the reduction in accommodations for actuation, linkages, and constraints for serially operated deployments, thereby allowing denser packing of launch kits. SAFIR could be envisioned, in principle, as the core of a larger telescope that would be achieve by adding elements to it later.

Higher performance structure: In-space assembly of telescopes provides some important performance advantages related to structures, both for launch and for operations. Lift capability, volume and diameter of the payload are simultaneously maximized. This overcomes a current limitation of deployed systems, which are often volumetrically limited and do not fully exploit the lift capability that is available. Assembled systems also provide superior dynamical performance during operation. This results from the fact that the frequency of the first bending mode of the structure has a significant impact on the overall performance of the observatory.

Testing economies: While the concept has not been fully defined, we can imagine a integration and test process in space that avoids a number of substantial costs that would be incurred to carry out the same work on Earth. First, no large, very clean, vacuum chamber is required to conduct tests. In the case of SAFIR, as well as many high priority astronomy missions, such a chamber would need to provide low temperatures as well. Rather, all components and subsystems would be tested individually and all interfaces verified on Earth. Final performance validation of both the structure and optics would be done in space.

Better reliability of deployment: Assembled systems can be verified step-wise throughout assembly, enabling alternate operations and workarounds to be exercised as needed before committing the entire system to operations. Alternatively, a traditional mechanical deployment process may also benefit from the availability of a mobile agent with sensing and some possibility of access for viewing and physical interaction. The reliability benefit in either case is keyed to the possibilities for intervention in cases of mishap or unexpected occurrence.

Extended mission life: The experience gained from the series of Hubble Space Telescope servicing missions indicates that a strategy of revisiting for redundancy replacement opens possibilities for an extended and productive operating life even for a large, complex, and delicate mission systems. The ability to changeout subsystems accommodates system failures and lifetime management (e.g. HST batteries, solar panels, and gyros). Opportunity for retanking of consumables (propellants and instrument cryogens) is another facet of the lifetime management capabilities that would be enabled by in-space operations.

Enhanced productivity: The Hubble servicing experience also showed that installing upgrades in technology as they become available can enhance mission productivity. This applies to science detectors and instruments particularly, but also support components such as data systems, power systems, control systems, etc. For SAFIR in particular, the current steeply increasing technology development curve for infrared sensors makes enormous science gains possible through upgrade opportunities.

Impacts to SAFIR Mission Designs

Modular design with in-space operations interfaces: Whether SAFIR is to be assembled or only serviced, by robotic-only or human-robotic coordinated operations, a modular design would be needed to allow component handling and integration in space. The modules would need interface designs that could be reliably handled by the agent capabilities available in the timeframe. For SAFIR it would seem that design for simple robotic module exchange or add-on would be most prudent, since the advanced human EVA capabilities in space would still be in development for human operations on the Moon. Modularity design for simple robotic-only module exchange or add-on would require interfaces that fit together with minimal requirements for preprocessing, and no requirement for dexterous handling or complicated interactions.

Approaches for assembly and servicing of components that operate at cold temperatures: SAFIR achieves its huge infrared sensitivity by being very cold. As such, the thermal characteristics of the observatory require special attention to contamination control. Outgassing of newly installed components, thruster plumes, and waste (gas and water) dumps from human facilities can all condense out on observatory components that are cold. Such condensation can seriously reduce observatory performance, both optical (because of coating opacity) and mechanical (because of interference on contacting surfaces in bearings.) This contamination may take place at temperatures that are well above the cryogenic operating temperatures, and even at temperatures that are amenable to servicing. While robotic servicing at the ~4 to 10K operating temperature could be considered, such efforts are likely to be very costly, and considerations for SAFIR should include strategies for safe thermal cycling of the observatory, as well as zone isolation.

With a large sunshield affixed, and solar panels on the opposite side of the sunshield from the telescope, special attention must be given to keeping the observatory warm while it is powered and being serviced. Keeping SAFIR powered up may not be easily separable from keeping it warm. Critical trades to be reviewed are opportunities for undeployment or removal of the sunshields during servicing, and the risks that are entailed, as well as rotisserie-mode heating of the observatory, and the difficulties that this would involve with respect to rendezvous and close-proximity formation-flying of service agents. The boom-deployment strategy for SAFIR (see Section X) may offer significant advantages in this regard, by allowing the telescope to be displaced to the side of the solar shield.

Safe operations near a large, delicate structure: The precision optical alignment of the SAFIR telescope and the fragility of the stretched mylar sunshields call for special attention to safe operations with an external agent. If left deployed, the mylar sunshield can be torn or otherwise penetrated by collisions with the in-service agents, or with debris released in the vicinity. In the baseline configuration, the sunshield is between the cold telescope and the warm spacecraft bus, so service opportunities on the observatory have to contend with a large shield that separates disparate regions that are the targets for such servicing.

Docking ports, spacecraft control connections: Although it may be feasible to use fly-around agents that attach to the observatory near where the servicing is to be done, and are monitored by a stand-off CEV where humans supervise and control the agents, the scale size of subsystems to be exchanged, and the range of attach points that need to be accommodated may argue for a more fixed base of operations. We envision a CEV or the servicing facility hard-docked to the observatory at a fixed location, ideally on the spacecraft bus end. The CEV or servicing facility would use a crane to reach around the sunshield to access the telescope. Such a strategy would allow servicing with a range of capable tools, all affixed to the crane. Presumably, several video vantage points would be provided, to give operators clear situational awareness. While a reach-around strategy poses complications, the sunshield can be considered to protect the telescope from contamination from the CEV, though optimal optical properties of the sunshield may be compromised by doing so. It may be assumed that the spacecraft bus offers structural advantages for docking, compared with a thermally optimized, and thus very lightweight telescope. Docking at the spacecraft bus allows for simple control connections between the CEV or servicing facility and the observatory, as well.

Dependence on service providers: Use of shared, multi-purpose, multi-mission designs, as well as interfaces, supporting systems, and processes usually entails some compromise from optimum single-point solutions to establish the commonality that is the basis for reuse and cost avoidance. A design to accommodate a service provider's interfaces, capabilities, and limitations should be well worth the burden of imposed requirements if the cost avoidance is substantial; otherwise there is no basis for departure from the traditional stand-alone approach.

Specific equipment for telescope in-space assembly and servicing: The SAFIR program would be responsible for providing unique equipment that would not be provided by the Exploration mission systems for their assembly and servicing of vehicles, habitats, depots, communications terminals, logistics supply, etc. This may entail specific handling and test equipment such as super-clean process controls, sunshield system for thermal stabilization, precision structure metrology, and astronomy instruments verification equipment. Some portion of this investment that is not built into SAFIR itself may be left behind at the supporting facility and made available for reuse by subsequent telescope assembly and servicing missions.

Venues for Astronaut-Assisted Deployment/ Upgrade/ Repair

While SAFIR is baselined for operations at Earth-Sun L2, the relevance of in-space opportunities for SAFIR in LEO should be addressed, if just because of the relative simplicity of getting there, and our experience with large structure development and servicing operations. We consider LEO to be an unfavorable locale for many reasons, however. The day-night cycle in LEO is highly disadvantageous for power management, as substantial batteries or at least fuel cells need to be used to allow continuous operation. These day-night cycles are of particular concern for an observatory like SAFIR, which relies on critically optimized thermal properties. The most significant problem is the thermal one; the structure will never get mechanically quiet unless special accommodations are made. These accommodations are likely to degrade performance at L2 and will add mass and cost if the telescope is going to be aligned and tested in LEO. Another issue in LEO is gravity gradient effects that will complicate testing of pointing performance, as will torques produced by atmospheric drag on the large sunshield. The LEO environment is potentially very risky for large mylar sunshields, in that debris can be expected that will produce penetrations (at a rate much higher than from micrometeorites at L2) and compromise the shielding efficiency. Finally, the delta-V required for transfer to L2 from LEO and back is large (3-5 km/s), and the accelerations and mechanical loadings entailed could require costly structural modifications to the observatory. As a result, the propulsion demands for both deployment from and return to LEO would require a propulsion module for the observatory of substantial size. Transfer from LEO to L2 and return for servicing also involves repeated transit through the radiation belts around Earth, entailing risk to sensitive components and requiring provisions for mitigating damage.

In view of these concerns, we may alternatively consider deployment and servicing opportunities on-site at the baseline operating venue of Earth-Sun L2. Human-attended opportunities at L2 are unlikely in the short term, at least because an early-phase CEV will not support such lengthy journeys which can be of order months (which in itself is a risk factor). Routine access of humans to L2 will have to contend with particle radiation risks from solar flares, and the lack of opportunities for quick emergency return as a result of such storms, equipment failure, or medical emergency. Opportunities for robotic agents at L2 are more feasible, and both replacement of entire subsystems and retanking of consumables appear increasingly feasible. But human control from Earth of robots at L2 involves several second delays that would reduce effectiveness of operation. As a result of this unavoidable control latency, there would be strong incentive to making such agents largely autonomous, which, while intrinsically feasible, will add cost and technical risk. By limiting the complexity of the servicing systems ,simple and well-designed servicing tasks could be performed reliably, for example module replacement or add-on, by limiting the complexity of the servicing systems but consequently would reduce the possibility for rescue or upgrade to an unproductive extent.

In view of these considerations, operations at Earth-Moon L1 have been proposed by a number of authors, and were the basis for the NASA Exploration Team (NExT) space architecture studies. The L1 location is at a distance of some 323,110 km from the Earth, or roughly 84% of the way to the Moon. The orbital dynamics at Earth-Moon L1 are similar to that of Earth-Sun L2, in that the location is semi-stable, and requires little station-keeping propulsion. L1 is of significant relevance to the Exploration agenda, in that access to the lunar surface at all latitudes is energetically equivalent, such that a trans-lunar base-station at L1 could offer considerable flexibility. While no spacecraft have yet been deployed to Earth-Moon L1 as a destination, our experience in Earth-Sun Lagrange point venues (e.g WMAP, SOHO, ACE) give confidence in our understanding of the requirements. Science operations at L1 are significantly less enabling than at Earth-Sun L2, however, because radiation from Earth and Moon cannot be reliably blocked along with the Sun, resulting in issues in scattered light and thermal management.

In addition to the relevance of Earth-Moon L1 to lunar exploration, of special importance is the fact that Earth-Moon L1 is connected to other solar system Lagrange points by pathways that are highly economical energetically. While it requires several months to travel between Earth-Moon L1 and Earth-Sun L2 on such a low-energy pathway, the departure and orbital insertion propulsion burden is remarkably modest – of order 100 m/s, a major advantage for a massive observatory. Return from Earth-Sun L2 to Earth-Moon L1 is simiarly economical. The programmatic convenience of the L1 site, “gateway” access to L2, and the fact that it is thermally much more stable than LEO, makes it an important venue, at least for integration, test, and servicing of science instruments.

Application of CEV and “Gateway” Concept at Earth-Moon L1

While the earliest concept of CEV will be aimed at LEO, the concept for the later model CEV can take humans to and from the lunar vicinity (in one concept, using a separate lander to carry them to and from the lunar surface) and presumably it could easily go to a Earth-Moon L1 libration orbit. Cargo vehicles would also have access to the lunar vicinity, surface, and libration point orbits. The Earth-Moon L1 libration orbit could serve as a staging area, a turning point for inclination changes, and a "gateway" to other solar system libration point orbits. Earlier architecture studies envisioned this site as the location for a human-visited in-space depot, or "shipyard" facility with resupply, refueling, servicing, and assembly capabilities.

Preliminary concepts for the early-phase CEV do not carry extensive accommodations for astronaut EVA other than emergency response: no airlock, no positioning crane, and minimal cargo accommodation volume. Conceptually, this system could be augmented by provision of an additional workstation module that could carry, for example, a teleoperated servicing robot, a suite of tools, some spare parts, or replacement modules for servicing. For this architecture to support SAFIR, four space systems would have to be brought together. SAFIR would have to be moved (for robotic servicing) to the rendezvous point in advance of CEV. The CEV augmentation workstation module would have to be outfitted with whatever SAFIR operation-specific equipment is needed; this would be completed by an earlier launch of a SAFIR-specific kit to rendezvous with and be captured by the workstation module. The CEV would then rendezvous with the workstation; the crew would operate the workstation equipment to load it with the specific servicing kit. Subsequently, the CEV and workstation with the kit installed would rendezvous with SAFIR and the crew would perform the needed servicing operation using the workstation equipment and the SAFIR-specific outfitting contents. SAFIR would have to accommodate a transfer stage for delivery to (and for servicing, a trip back from) its operational site in a Sun-Earth L2 libration orbit. For transfers between L2 and a L1 servicing site, this transfer stage may be quite modest in capability, and may be the same propulsion system that is used for halo orbit management at L2.

The later CEV could bring humans to the gateway facility whenever it was slated for operations. The facility need not be permanently staffed by human operators. However, it would incorporate basic space platform utility and logistics accommodations to keep the systems available to support the visiting missions. Indeed, some of the early operations of the facility could be conducted in a robotics-only mode, teleoperated from the CEV, which can be docked or station-keeping nearby, conducted from human presence sites on the lunar surface, or remotely controlled from operations centers on Earth. The initial facility outfitting could include later models of the robotic servicer systems used earlier in LEO, on the lunar surface, and on Mars during the testbed and precursor mission phases. After the gateway facility has become established as a reliable and robust operations base, general-purpose and reusable capability equipment designed for multiple-mission applications would also be provided and integrated as needed to support ongoing programs. A human life support and safety capability could be integrated later to the facility based on habitat designs used on the lunar surface and adapted for use in zero-gravity and space environment.

To the extent that the gateway facility will play a major role in an ambitious lunar program, special planning will have to be done to accommodate shipyard issues, such as flotilla formation maintenance, hazard avoidance, and contamination mitigation. While such a busy gateway facility would offer SAFIR flexibility in in-space tasks, the price for that convenience is the resulting congestion and contamination potential.

Of some interest for a gateway facility and astronomical telescopes is the potential for in situ checkout before they are sent back to L2. L1 is, itself, a potentially cold place, in that the solid angles subtended by the Earth and Moon are still quite small, and passive cooling there, in which sunlight is shielded from the telescope will not be highly inferior to that available at L2. It seems clear that all warm spacecraft systems (communications, stabilization, cooling etc.) can be fully checked for SAFIR at L1, and ideally much of the science payload can be functionally tested as well. Using on-board cryocoolers to put the infrared sensors into their operating range, a slightly warmer-than-spec telescope will allow pointing, tracking, imaging, and spectroscopic functions to be verified, though with higher background noise, and scattered light. The optical alignment of the telescope could, in principle be verified, and diffraction-limited performance assured.

Scenario for SAFIR Servicing at an Earth-Moon L1 Gateway

In this section, we present a highly simplified strawman scenario for SAFIR servicing at the Earth-Moon L1 gateway. Our extended study will use a picture (Figure XI-1) as a starting point for more detailed in-space servicing plan for the observatory.

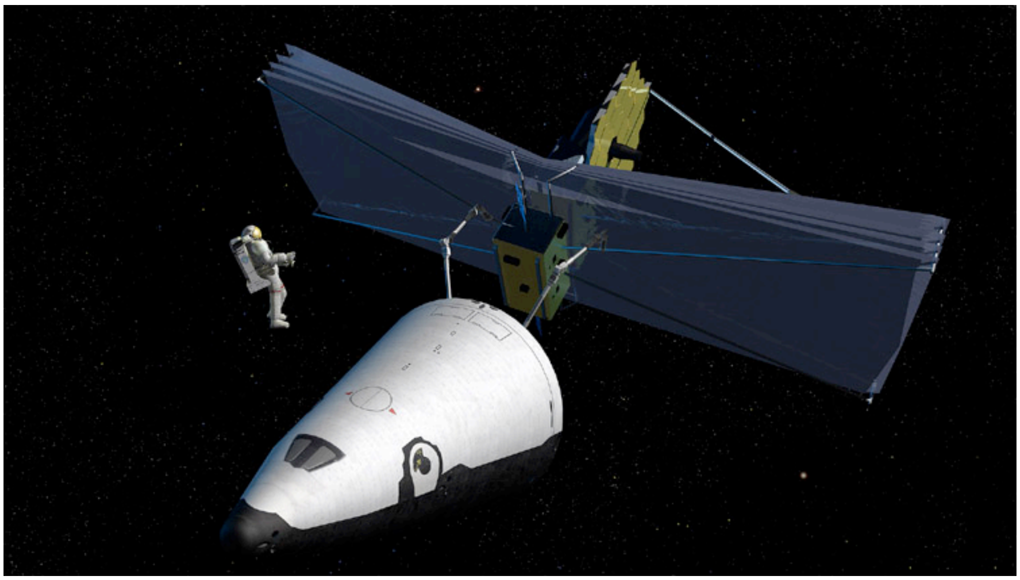

Figure XI-1: SAFIR is shown being serviced using a CEV. The CEV mates to the observatory at the spacecraft bus section, and uses cranes to service the telescope. Unless lengthy cranes are used, or boom deployment of the telescope is employed, EVA may be required to access the instrument section of the telescope. Conversely the solar shields could be removed to allow direct access to the ISIM from the CEV.

SAFIR is retrieved from L2: The SAFIR cryocoolers are shut down, the instruments are set to a safe configuration (apertures closed, etc) and the observatory is allowed to warm up. The observatory is canted to allow sunlight into the sunshield vee. Warming up the observatory offers some insurance against contamination by thruster plumes needed for retrieval. The observatory is removed from L2, and sent on a trajectory to L1, using on-board thrusters. Another option is for retrieval by a separate tug that docks with the observatory at L2. This would be needed if the on-board propulsion system were inoperable or undersized. After months of transit with precise navigation and slight trajectory corrections, SAFIR arrives in the vicinity of Earth-Moon L1. Upon L1 insertion, SAFIR is put into a slow rotisserie mode to finish bakeout of contaminants accumulated during the operations lifetime. A key thermal trade for servicing is whether to keep the sunshield, or consider it expendable. If it is to be jettisoned and replaced, it is released into a safe trajectory before SAFIR enters the capture zone of the servicing facility.

Pre-service inspection: While SAFIR is still at a stand-off position relative to the servicing facility at L1, fly-around robotic agents based from the facility provide a clear overall survey of the observatory to assess its structural condition and abnormalities. Rotisserie mode provides illumination for all parts of the observatory. Inspection is used to finalize the servicing plan and determine if any updates to the servicing mission objectives are necessary. A servicing logistics module carrying all the servicing components and agents will have been launched to couple with the CEV or servicing facility before SAFIR arrives.

CEV or agent connection: The CEV, or a mobile or extensible operating agent of the servicing facility, is deployed to rendezvous with and capture SAFIR, bringing the spacecraft bus interface to dock with the CEV or servicing facility. Here direct power and control connections are established and all the servicing tools and replacement parts are accessible. Functionality and safety checks are established. As shown in Figure XI-2, a boom-deployment architecture for SAFIR is highly enabling in this regard, as the service agent is able to reach around to the back end of the telescope without removal of the sunshield, and without a highly articulated crane.. Were this architecture not employed, a riskier EVA or fly-around rendezvous with formation flying might be necessary to reach the telescope, or even wholesale removal of the solar shields. The latter option may be considered a standard servicing upgrade, however, to replace a sunshield with degraded reflectivity or meteorite perforations. In this case, the sunshield would be discarded before servicing on the telescope would even begin.

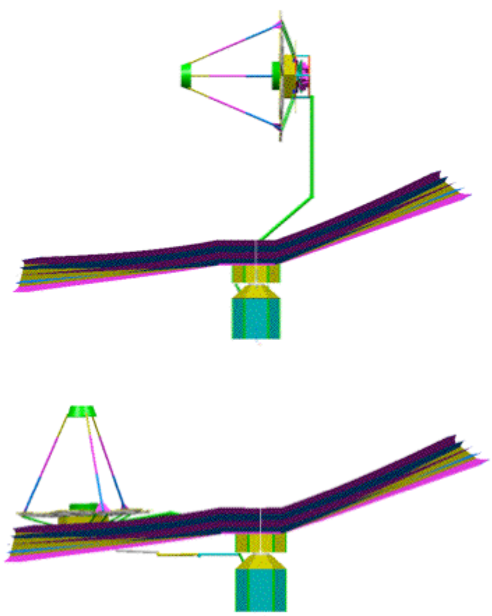

Figure XI-2: One of the advantages of boom-deployment architecture for the SAFIR telescope is in allowing observatory servicing to be done advantageously. In this schematic, the telescope (in operational configuration at top) is shifted to the edge of the sunshield for servicing (at bottom), allowing the CEV crane to reach the instrument housing at the back of the OTA, and putting the telescope into sunlight.

Subsystem replacement: An extensible agent, perhaps a reconfigurable crane, uses tools to sequentially remove and replace individual subsystems as required. Sunshield patching or wholesale replacement is the last item. It is even possible to consider recoating of the reflecting surfaces, using the high vacuum to allow efficient evaporative coating deposition.

Retanking: The station-keeping propulsion system is serviced either with replacement modular components or retanked.

Intervention-enabled redeployment: While SAFIR is attached to the CEV or servicing facility, major deployments (e.g. new sunshield) are commanded. Active mobile agents are available for mechanical intervention if something jams or sticks.

Early system checkout: SAFIR is released from the servicing facility to the stand-off position to allow a system functional test. The observatory is put into a sun-oriented attitude, allowing the inner shield and telescope to cool. All SAFIR systems are powered up and functionally tested. Basic pointing and stabilization tests are conducted on the telescope while it is still warm. Cooldown profiles are compared to expectations and the experience base. When the basic tests are completed satisfactorily, the CEV or mobile extensible agents are withdrawn agent from SAFIR.

Detailed system checkout: SAFIR is allowed to cool while in the vicinity of L1, reaching temperatures below 50K. (The Earth and Moon are not necessarily behind the shield.) The built-in active cryocoolers put the cooled sensors into their operating range. The scientific instruments are exercised, and performance is matched to expectations for performance at the temperature achieved.

Return to L2: Upon full and satisfactory completion of all performance tests, the SAFIR observatory departs from L1 and travels to, and is injected back into L2. SAFIR Science operations restart.

Conclusion

We have presented here a broad overview of the advantages, issues, and concerns that in-space operations for servicing SAFIR would involve. A more detailed review must await a better understanding of the implementation plan for the human and robotic elements of the Vision for Space Exploration, such that leveraging opportunities will be made clearer. CEV design, and the value of L1 gateway operations to the Vision are critical factors in this regard.